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Model of a System-Wide Domestic Hot-Water Distribution System in a Multi-Resident High-Rise Building

To reduce the environmental impact and cost, energy and water consumption of multi-resident buildings should be improved while ensuring resident comfort. Inefficient mixing of hot and cold-water streams and a non-optimal domestic hot-water (DHW) distribution system design can cause higher energy consumption, component failures, and dissatisfied residents. An OpenModelica (OM) system-wide model of a 14-story building consisting of a controlled-loop injection (CLI) device and a DHW distribution system is presented. The OM results are validated against field measurements at discreet locations within a single-zone closed-loop circuit to ensure the validity of time-varying temperature and flow-rate. The study demonstrates that OM is a useful engineering tool to model single and multi-zone high-rise buildings that allows advanced analysis, including system-wide optimization, advanced on-demand controls, and energy and water-usage efficiencies.

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Introduction

Energy consumption together with resident comfort and safety in high-rise buildings (e.g., multi-dwelling buildings) can be challenging. The residential building sector consumes 11–35% of total energy in most countries [1]. In the United States, domestic hot-water (DHW) use in high-rise buildings is the second-largest component of residential energy consumption, after space heating [2]. DHW temperature control needs to ensure resident safety and comfort while meeting building regulations regarding Legionella and scalding. There are four main areas in DHW distribution systems that affect energy consumption in high-rise buildings [3,4]:

- (1) water heater inefficiency,
- (2) water heater losses,
- (3) distribution system losses together with the mixing device efficiency (mixing of hot and cold-water streams under variable-demand), and
- (4) energy consumption at the end-user point.

With regard to energy consumption, although daily, monthly, or annual energy (and water), demand has been extensively studied in buildings [5], there is still a need for studies on the long-term effect of temperature fluctuations of a DHW system (since most failures occur in hot-water piping [6]) to better understand and predict the life cycle of the system. These studies are limited by access requirements and cannot be performed in situ. While patterns of hot-water usage are essential for a more reliable assessment of energy requirements [7,8], energy and water-use inefficiencies have been challenging to decouple for a system-wide DHW distribution system [3].

One reason for high-energy demand in DHW distribution systems is the need to deliver hot water to a thermostatic mixing valve (TMV) from a domestic storage tank at 55–60 °C (140 °F)

to reduce the risk of Legionella [9]. While much work has been done on studying domestic hot-water storage tanks [7,10,11], very few studies have examined the mixing device (independently) along with the piping layout and architecture in high-rise buildings to study the implications on energy and water-usage efficiency. Work on the efficiency of mixing devices has mainly focused on thermostatic mixing valves (TMVs) for industrial applications (using computational and experimental methods) to study thermal fatigue caused by the mixing of hot and cold streams inside power plants, petrochemical plants, electronic cooling devices, etc [10], [12–19]. With these studies, a constant hot and cold flow was used, even though the fluctuating nature of hot-water demand in high-rise residential buildings is the primary challenge of understanding resident demand. Additional work has included one-dimensional (1D) modeling of a TMV to evaluate the response time of the system and develop advanced control systems [10,20]; however, no field data were provided to support the model or to evaluate TMV implications on DHW system energy and water-usage efficiency.

To account for the fluctuating nature of hot and cold streams, a field study compared the thermostatic mixing valve (TMV) to a controlled-loop injection (CLI) device in a 14-story high-rise building [4]. The results showed that CLI not only provided better temperature control throughout 24 h, but also reduced water temperature below 49 °C (120 °F) to save energy during low-demand periods [4]. This study also reported that the building's recirculation flowrate was 40% higher using the CLI installation, which was indicative of less pressure drop in the DHW loop giving further insight into energy and water-usage improvements [4].

There is also a need to optimize DHW distribution systems of existing high-rise buildings and provide additional insight into energy conservation and water-waste reduction techniques for the design of new condominium builds in a non-intrusive manner. A validated design tool that allows for the investigation of different DHW piping layouts and architectures (e.g., recirculation line), component sizing, and more efficient on-demand control systems are crucial to this goal.

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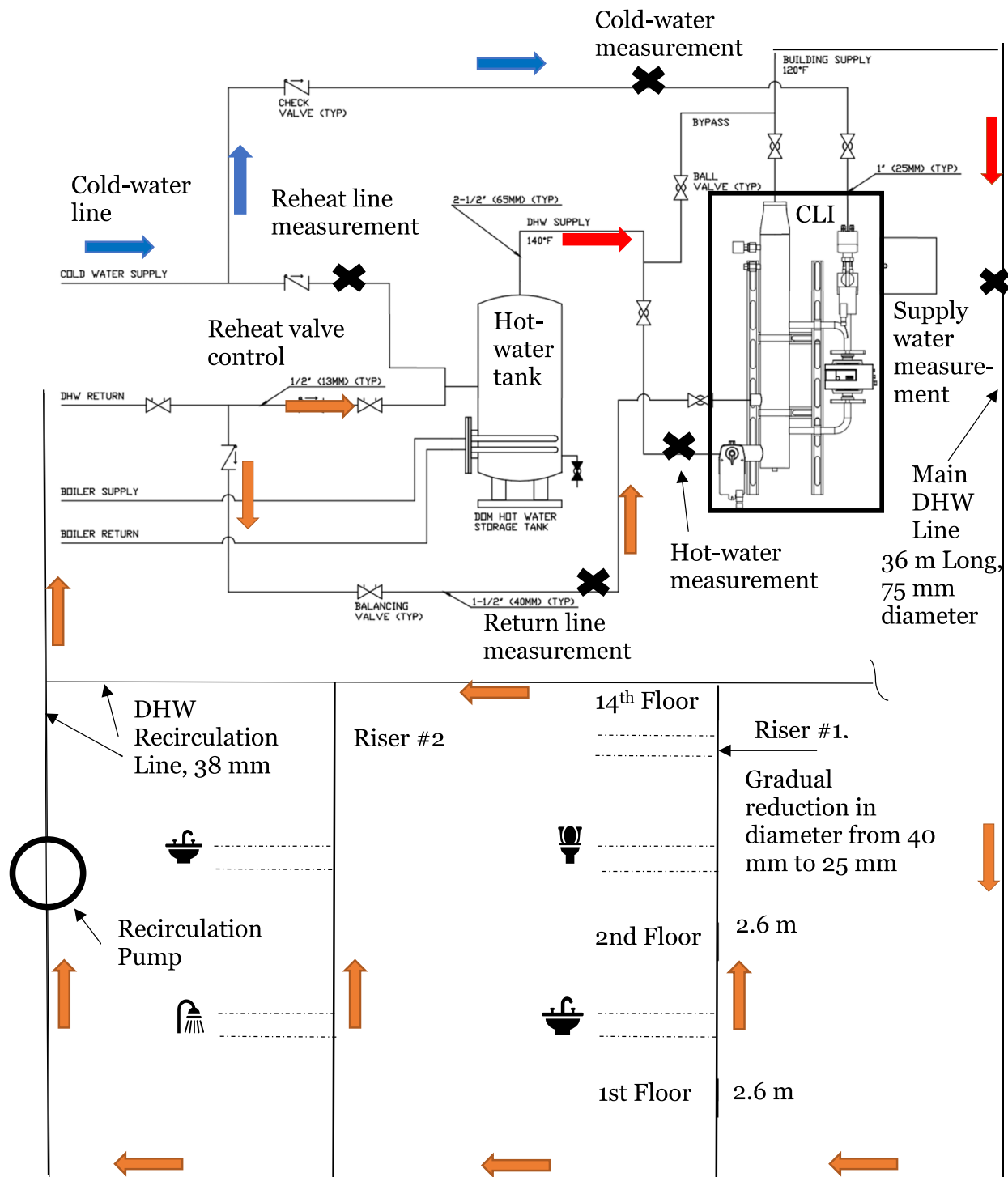


Fig. 1 Mechanical drawing of a mechanical room (CLI device and domestic hot-water tank) and the DHW distribution system for a single-zone high-rise multi-dwelling building. The black multiplication symbols show field measurement locations.

Although there exist models which analyze energy losses from hot-water distribution pipes in residential homes [21,22] and studies that focus on low-temperature district heating for buildings [23], there are no field-validated models that study the system-wide performance of a DHW distribution system in high-rise buildings (particularly for North America).

The present study presents a single and multi-zone OM model for an onsite DHW system (using a CLI device for mixing the hot- and cold-water streams) that uses random-demand modeling based on the statistical variation obtained from field results to predict flow,

pressure, and temperature fluctuations in the flow circuit over the 24 h. This research aims to quantify the following:

- (1) single-zone performance assessment for a DHW system by
 - the development of a field-validated model to study flow and temperature inside a closed-loop circuit.
- (2) multi-zone performance assessment for a DHW system by
 - energy savings resulting from replacing an electric booster heater (EBH) with an in-line heat-exchanger (HE). These systems are typical in multi-zone high-rise buildings to

maintain the water temperature at 49 °C (120 °F) in lower zone loops.

It is shown that this approach provides improved insight into energy and water usage that is impossible with field tests and is more relevant to North American building standards.

Methodology

The OM DHW distribution model was developed using the Buildings and Fluids library [24,25]. Both libraries were developed to model building energy and control systems.

Numerical Modeling. A 14-story (297 units) building with a single recirculation loop (i.e., single-zone high-rise building) was selected for this study [4], where time-varying temperature and flow field data to aid with model validation have been obtained. A schematic of the mechanical room consisting of a Controlled-Loop Injection (CLI) device and a hot-water storage tank (located on the roof of the building) together with the domestic hot-water (DHW) distribution system is shown in Fig. 1.

The field data were captured (FD-R series clamp-on flowmeters) over 7 days for the CLI device installation [4]. Field measurement locations include the following [4]:

- (1) DHW main supply line to the building (immediately downstream of the CLI device),

- (2) DHW line from the hot-water storage tank to the CLI device,
- (3) cold line to the CLI device, and
- (4) return line connecting back to the CLI device.

The DHW system-wide model does not depend on inputs from field data; that is, the flow is generated using a variable-demand scheme by opening and closing multi-unit faucets (i.e., flow control valves (FCVs)). For accurate model validation, the DHW system together with CLI was modeled as close as possible to the physical DHW distribution system. The single-zone configuration shows that the DHW main supply line connects to the mixing tank (CLI device) out-port and extends along floors 1–14 for ≈ 36 m (2.6 m/floor). The building configuration includes a vertical piping system (three main risers) to deliver hot-water (at a maximum pressure of $p_m = 550$ kPa, [26]) to the multi-dwelling units. During demand periods, the DHW recirculation line delivers flow back to the CLI device, thereby mixing with the hot and cold-water inside the mixing tank. For no-demand periods (e.g., overnight), the CLI device control system allows a small portion of the return flow to be replaced by the hot water (i.e., the flow goes back to the tank) to maintain the temperature at ≈ 49 °C in the main supply line [4].

The equivalent OM model is shown in Figs. 2 and 3. Figure 2 shows the mechanical room consisting of hot- and cold-water sources, piping, valving, the CLI device and a controller. Similarly, Fig. 3 shows the DHW distribution network consisting of a 76.2 mm (3.00 in.) main supply line distributing water to the three main risers. The main risers connect to branch segments

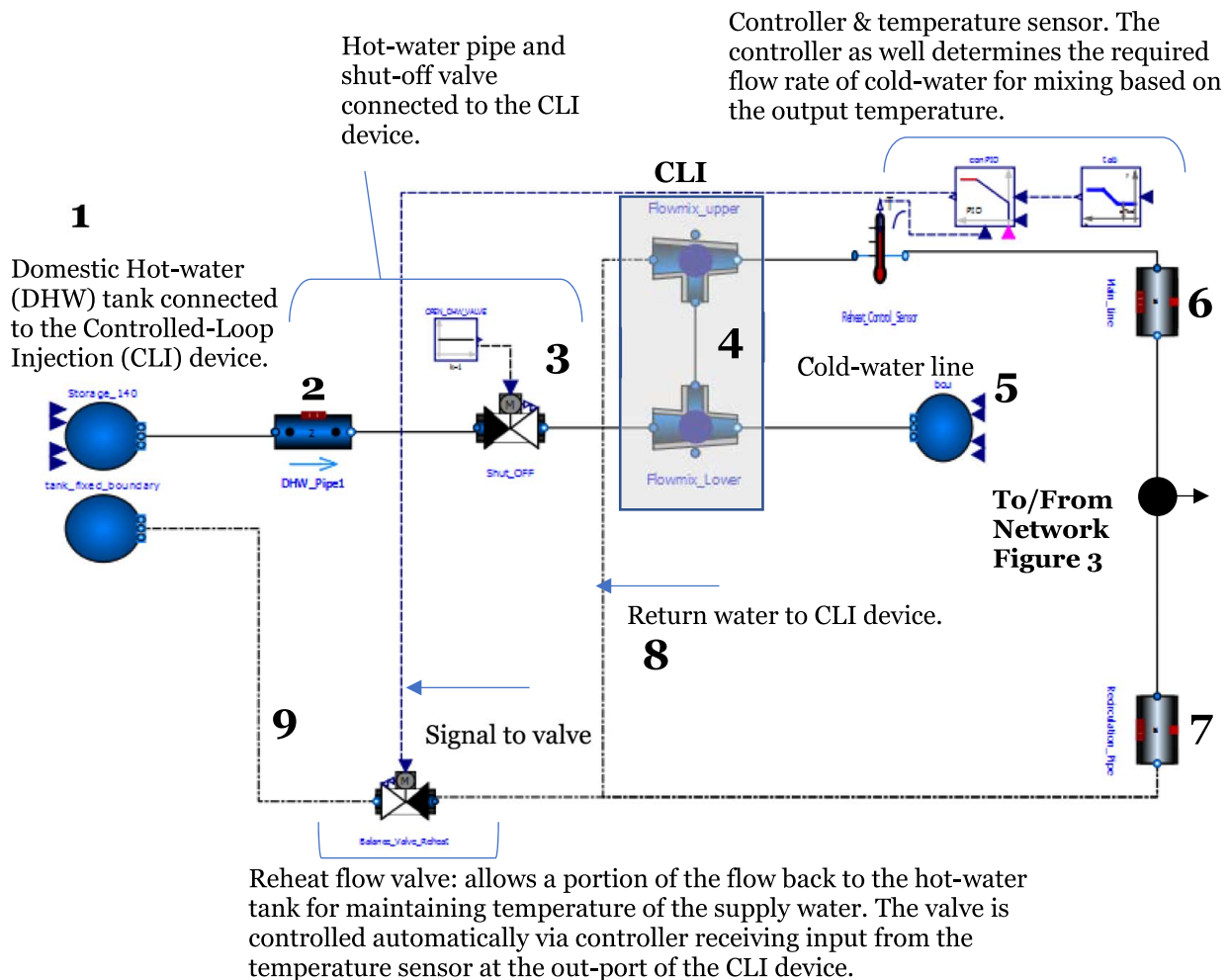


Fig. 2 Simplified OM single-zone mechanical room Model. The full-model is included in the Appendix and was simplified for clarity.

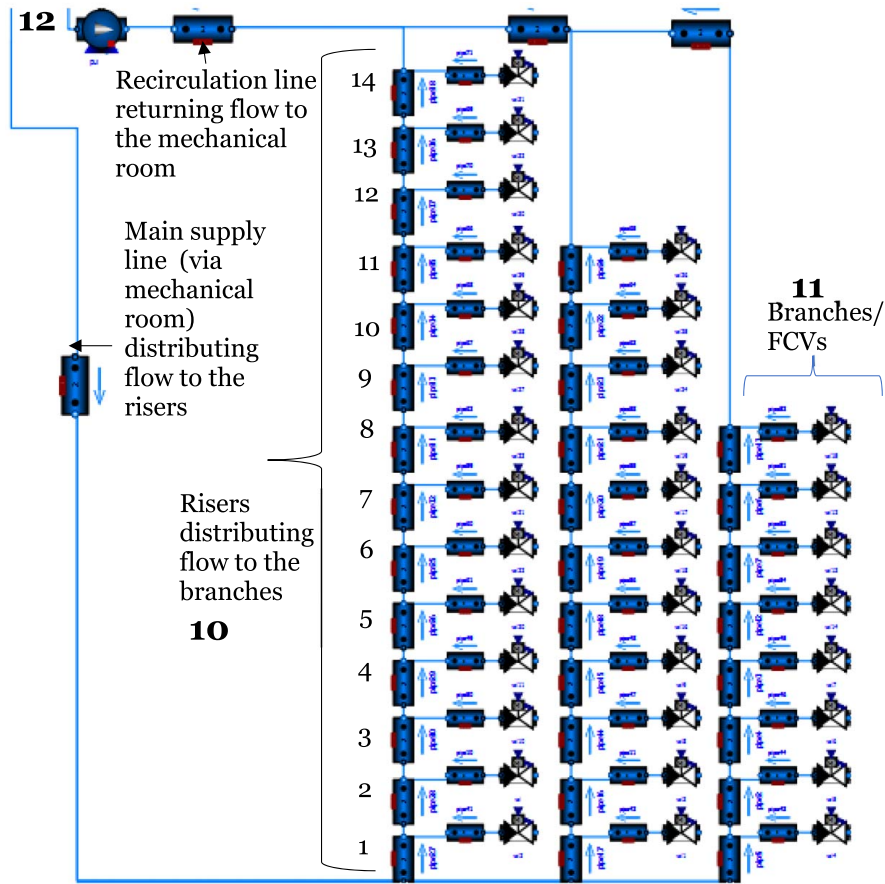


Fig. 3 OM DHW Distribution Network Model

delivering flow to multi-dwelling units and the recirculation line. Nominal specifications for the mechanical room and the DHW distribution network are given in Table 1.

Modeling Variable-Demand. The flow field data captured inside the domestic hot-water (DHW) main supply line was scaled with the maximum flowrate ($Q_{\max}$) to determine non-dimensional values (i.e., 0.5 and 1.0). The values were used to control the flow control valves (FCVs) connected to the riser's branches upstream of the multi-dwelling units. To ensure that FCVs correctly model demand (Q_{demand}) over 24 h, the total recirculation flow ($Q_{\text{recirc}} = Q_{\text{reh}} + Q_{\text{ret}}$; where Q_{reh} is the reheat flow to tank and Q_{ret} is the return flow to CLI device) was subtracted from the main supply flow (Q_{supply}). A timetable block (from the Buildings Library) in OpenModelica (OM) was used to model the variable-demand over a 24-hour period (i.e., 0.5 is 50% open—Fig. 4). Figure 5 shows non-dimensional flow, $Q^* = Q_{\text{demand}}/Q_{\max}$, versus time (in hours) over 24 h. The red line shows no-demand during night (i.e., midnight to 5 a.m.). The yellow indicates sporadic demand. The variable-demand scheme only controls the flow demand profile over time and not the flow amplitude and its distribution inside the piping network. The latter is solely controlled by the piping architecture, static pressure, and friction losses [26].

Heat-Transfer Model. Heat loss along the domestic hot-water (DHW) distribution network was modeled using thermal conduction blocks. The thermal conductivity coefficient (κ) based on copper pipe (type-L) is 401 W/mK [27]. The conductance for the pipe is expressed as $G = 2\pi\kappa L / \log(r_{\text{out}}/r_{\text{in}})$, where L is the length of the pipe and the corresponding heat is $Q = G(\Delta T)$, with ΔT

as the temperature difference between the inside and outside pipe walls [24]. Conductive heat transport between the fluid bulk flow and its environment (i.e., 22 °C) was used to find heat loss inside the DHW distribution network away from the storage tank.

While a single-zone distribution system with controlled-loop injection (CLI) does not reheat the primary recirculation loop (due to reheat valve controls), multi-zone high-rise buildings do require a reheat source in lower zones. A low-zone loop (secondary loop duplicates primary loop) with a heat-exchanger (HE) and an electric booster heater (EBH) was added to the present model (Fig. 6), to simulate a low-zone configuration in a multi-zone building. This allowed the calculation of energy consumption for both heat sources. A typical low-zone loop requires secondary heating during no-demand since water cools. For the EBH model, heat loss inside the primary recirculation loop (during no-demand) is first validated against field data. The reheat valve is disabled for all return water to go back to the CLI device (no exchange of return water with hot water). To determine the heat energy transferred to the water to maintain a loop temperature of 49 °C, the following relation is used [28]

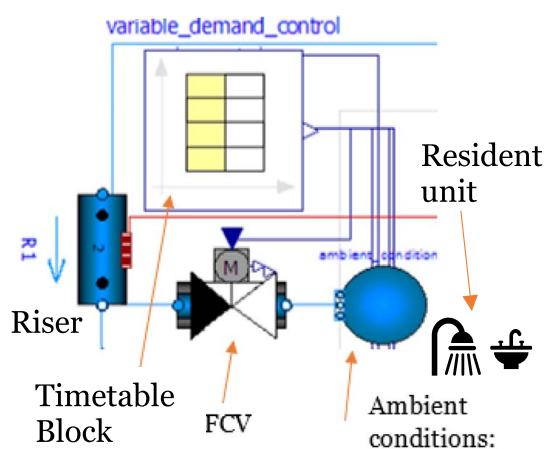
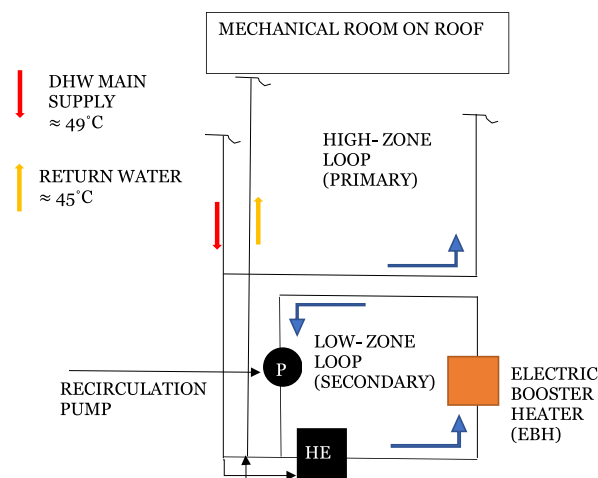
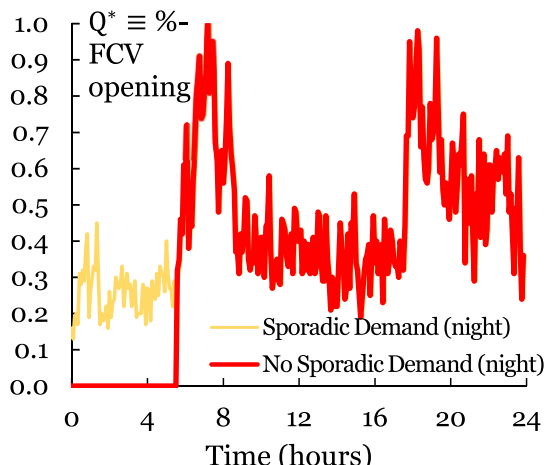
$$\dot{Q} = \dot{m}c_p\Delta T \quad (1)$$

where $\dot{Q}$ is heat energy added to water, $\dot{m}$ is the mass flowrate, c_p is the specific heat, and ΔT is the change in temperature. The Open-Modelica (OM) Buildings electric heater is adjusted to force the outlet temperature to 49 °C and compute $\dot{Q}$. During no-demand (e.g., overnight), $\dot{Q}$ remains constant and the total amount of heat transfer can be computed as $Q = \dot{Q}\Delta t$, where Δt is the cooling time interval [28]. For the HE model, the EBH is removed from the low-zone loop. As shown in Fig. 6, the main supply line

Table 1 Mechanical room and DHW distribution network nominal specifications

Component	No.	Estimated length (mm)	Standard size diameter (mm)	Wall thickness (mm)	Insulation type	Material
DHW storage tank	1	n/a	n/a	n/a	Foam-and-foil wrap	n/a
Hot-water pipe	2	2000 (2 m)	63.5 (2.50 in.)	2 (0.080 in.)	Foam-and-foil wrap	Copper type L
Fail-safe shut-off valve	3	n/a	n/a	n/a	n/a	n/a
CLI device	4	1000 (1 m)	100 (0.1 m)	n/a	n/a	Stainless steel valve construction
Hot inlet		n/a		n/a	n/a	
Cold inlet			25.4 (1.00 in)	n/a	n/a	
Return inlet			38.1 (1.50 in)	n/a	n/a	
Supply outlet			76.2 (3.00 in)	n/a	n/a	
Cold-water source	5	n/a	n/a	n/a	n/a	n/a
DHW main supply line	6	36 m	76.2 (3.00 in)	2.2 (0.090 in)	Foam-and-foil wrap	Copper type L
DHW recirculation line (total flow)	7	n/a	38.1 (1.50 in)	1.5 (0.060 in)	Foam-and-foil wrap	Copper type L
DHW return line (back to the CLI device)	8	3500 (3.5 m) ^a	38.1 (1.50 in)	1.5 (0.060 in)	foam-and-foil wrap	Copper type L
DHW reheat line (back to the tank)	9	1000 (1 m) ^a	19.0 (0.75 in)	1.1 (0.045 in)	foam-and-foil wrap	Copper type L
Risers (vertical piping)	10	36 m	40 to 25 gradual reduction	1.5 (0.060 in)	foam-and-foil wrap	Copper type L
Branches (connected to resident dwellings)	11	1000 (1 m)	12.5 (0.50 in)	1.0 (0.040 in)	foam-and-foil wrap	Copper type L
Recirculating pump	12	Series H63 high-duty in-line (Armstrong), 0.38 kW, 1800 rpm				
EBH	13	18-kW Heater				
HE	14	Constant heat-effectiveness, $\epsilon = 0.8$				

^aReturn line length is measured from where the recirculation line splits into reheat and return line segments.

**Fig. 4 Variable-demand control via FCVs****Fig. 6 Typical Multi-zone building configuration****Fig. 5 FCVs Control Scheme (Color version online.)**

connects to the HE and exchanges heat with the secondary loop (low-zone) through the 24 h. Supply water exits the HE and is returned to the CLI device with a portion of the water returning to the storage tank to maintain supply temperature at 49 °C (since heat was transferred to the secondary loop). The HE unit transfers heat to the secondary loop by amount $\dot{Q} = \dot{Q}_{\max} \epsilon$, where $\epsilon = 0.8$ is constant effectiveness. To compute energy consumption (i.e., gas consumption in kWh), the DHW storage tank is considered as an open control volume (i.e., energy required to heat the water is added to the system via the tank boundary) where the energy and mass balance for a steady-flow system are as follows [28]:

$$\begin{aligned} \dot{Q} &= \dot{m}_H h_H - \dot{m}_C h_C - \dot{m}_R h_R \\ \dot{m}_H &= \dot{m}_C + \dot{m}_R \end{aligned} \quad (2)$$

where, respectively, H , C , and R are hot, cold, and reheat streams to and from the tank. The specific enthalpy (h) for liquid water is selected based on the temperature of the water (i.e., $h@49^\circ\text{C}$ for hot water). The storage tank is kept at approximately 450 kPa

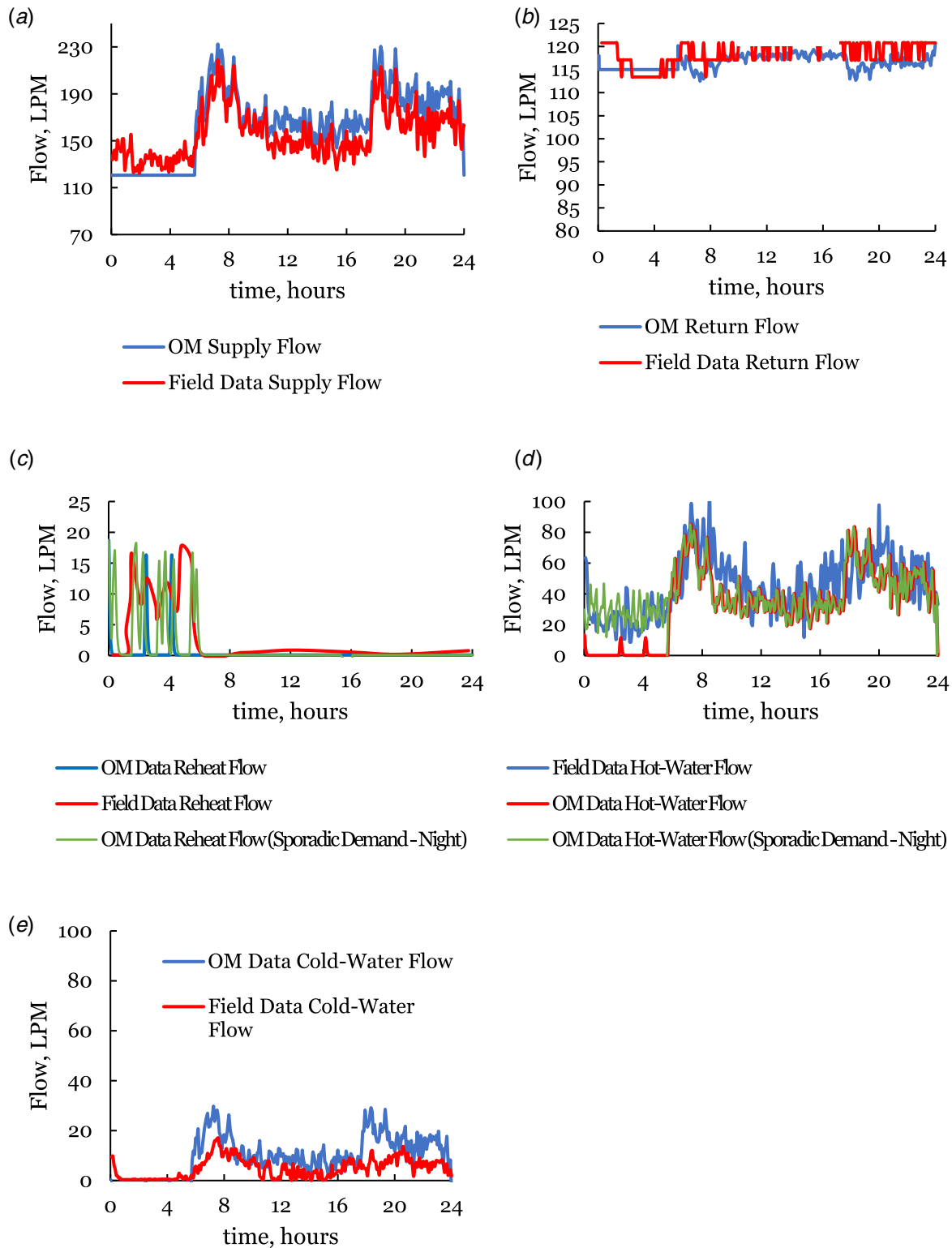


Fig. 7 OM Model validation data for Flowrate: (a) supply flow, (b) return flow, (c) reheat flow, (d) hot-water flow, and (e) cold-water flow. Note: 0 represents midnight.

(abs) corresponding to saturation temperature of 235.7°C (456.39°F) [28]. Since all temperatures of streams are below this value, the water in all three streams exists as a compressed liquid and can be approximated as a saturated liquid at the given temperature [28].

Openmodelica Errors

The experimental uncertainty of the Keyence Flowmeter FD-R80 is $\pm 3\%$ of RD for temperature and $\pm 2\%$ of RD for flowrate. To determine the random error of the OpenModelica (OM) results

under steady-flow demand, flow data (Q) were compiled from several simulation runs. The normalized error was computed as $\epsilon^* = \epsilon_{OM}/|\bar{Q}| = t_1(\text{r.m.s. } Q')/\sqrt{N}$, where $t_1 = 1.96$ represents confidence of 95%, r.m.s. Q' represents the varying component of flow (as a result of several trials) and $N=10$ is the number of runs to reach statistical convergence for Q (within experimental uncertainty)[29]. The normalized error was found to be $\pm 0.7\%$ for flow. Similarly, for temperature, the normalized error was found to be $\epsilon_{OM}/|\bar{T}| = \pm 1.2\%$. Both values are within the uncertainty of the field measurements.

Results and Discussion

Model Validation of Single-Zone Loop. The DHW distribution system performance was validated using OM flow and temperature data (over 24 h) based on field measurements at selected locations (indicated in Fig. 1) inside the closed-loop flow circuit. For the OM results, the emphasis was placed on the mean behavior of flow and temperature and not random fluctuations. Figure 7 compares the supply, return (back to CLI device), reheat (flow back to the storage tank), hot- and cold-water flows, respectively. Similarly, Fig. 8 compares temperature data of the supply and return flows all through the 24 h. The supply and return flows match well, reaching maximum values of ≈ 230 LPM (62 GPM) and 120 LPM (32 GPM), respectively. The constant supply flow during no-demand (i.e., nighttime) for the OM model represents recirculation flow exempting infrequent demand. Additional differences in the flow data between the OM model and field measurements are due to experimental error and modeling accuracy of major/minor piping losses. Since the controlled-loop injection (CLI) device works on the principle of energy-saving mode, the reheat flow reaches a maximum value of ≈ 15 LPM (4 GPM) during nighttime to ensure the distribution network water temperature does not fall below $\approx 45^\circ\text{C}$ (113°F). The profile difference between OM and field reheat flows (for no-demand at night) is attributed to valve response time, type of valve control, and sporadic demand during nighttime not captured

by the model. Sporadic demand during the night is also reflected in Figs. 7(c) and 7(d) for comparison purposes and matches the field results well. The programmed temperature drop during nighttime is shown in Fig. 9(a), where both the model and field data display a minimum temperature of $\approx 46^\circ\text{C}$ (115°F) prior to early-morning demand-increase. The temperature trends during nighttime do not show a close match between the data sets. OM models reheat inside the circuit (e.g., a portion of return flow replaced by hot water) using ON/OFF controls to fully open/close an FCV upstream of the storage tank. When the FCV closes, no hot water enters the flow circuit and the recirculating water cools at a constant rate. In contrast, the field circuit uses an FCV that gradually opens/closes (with delayed response time) to redirect a portion of the flow to the storage tank until a set temperature is attained in the supply line (prioritizes closure of reheat FCV over larger cold flowrate to maintain 49°C for infrequent demand). Also, temperature fluctuations observed in the field data are because of sporadic hot-water demand during nighttime. During early morning, the reheat valve closes since the temperature in the main supply line reaches $49 \pm 2^\circ\text{C}$ ($120 \pm 2^\circ\text{F}$) as a result of hot-water flowing from the tank. There is much less variation in the temperature for the OM model during demand given the tighter tolerance range of $\pm 0.25^\circ\text{C}$ from cold-water injection controls. Another reason for the supply and return temperature differences is the lower variances in the cold-water temperatures for the OM results. The return flows show the consistent temperature at $\approx 48^\circ\text{C}$ (118°F) once the reheat valve is closed shut in early morning.

Moreover, the hot- and cold-water flows are in good agreement between OpenModelica (OM) and field measurements. For hot water, the main difference is that OM results do not include infrequent demand during night time. The cold-water for the field data shows a lower (≈ 10 LPM) flowrate during early morning and late evening because there is a higher temperature set-point of 50°C for the model (see Fig. 8(a)).

Multi-Zone Energy Assessment: Electric Booster Heater Versus Heat-Exchanger. The low-zone loop temperatures and the electric booster heater (EBH) energy consumption over 24 h are shown in Fig. 9. With the EBH installation, the various OM pipe segments show a mean temperature of $48.7 \pm 0.5^\circ\text{C}$. Pipe 4 shows a slightly lower mean temperature (i.e., 48.4°C) due to heat loss along the loop downstream of the EBH. Figure 9(c) shows energy consumption $\dot{Q} \approx 5000$ J/s (5 kW) during no-demand (midnight to 6 a.m.) when the loop cools as the worst-case scenario. For comparison, consumption based on sporadic demand during the night and demonstrates a maximum difference of 10–20% with respect to no demand. For demand during night, the hot-water mixes with the loop water, increasing water temperature and decreasing energy consumption by the EBH unit. Furthermore, during high demand (early morning and late evening), energy consumption goes to approximately zero since the mass flow (at 49°C) from the supply line mixes with recirculation flow. Results as well show $\dot{Q} \approx 3000$ J/s (3 kW) during midday (i.e., 10 a.m.—4 p.m.) when demand reduces. For comparison, Fig. 10 shows inlet/outlet temperatures of the heat-exchanger together with the reheat flow (mass flow returning to the tank) and energy consumption, respectively. Additional reheat flow (to maintain supply flow at 49°C) results from energy loss in the supply flow through heat-exchange with the low-zone loop. Figure 10(a) shows inlet supply (i.e., a1) and outlet return (i.e., a2) temperatures at $\approx 49^\circ\text{C}$ and $\approx 47.5^\circ\text{C}$ at no-demand, respectively. All resident DHW demand (i.e., 6 a.m. to midnight) supply flow enters the low-zone at roughly 49°C and increases the water temperature. The amount of heat-exchange inside the HE during demand predominantly depends on the ratio between supply and zone recirculation mass flows. The energy consumption to maintain the low-zone water temperature at $\approx 49^\circ\text{C}$ was computed from an energy balance of the storage tank (i.e., Eq. (2)). Figure 10(b) shows reheat flow for single and multi-zone configurations over

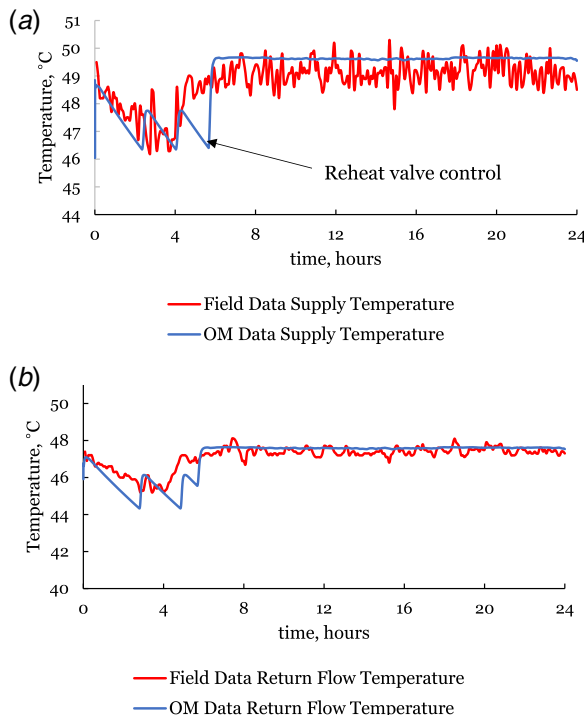


Fig. 8 OM Model validation data for temperature: (a) supply flow and (b) return flow. Note: 0 represents midnight.

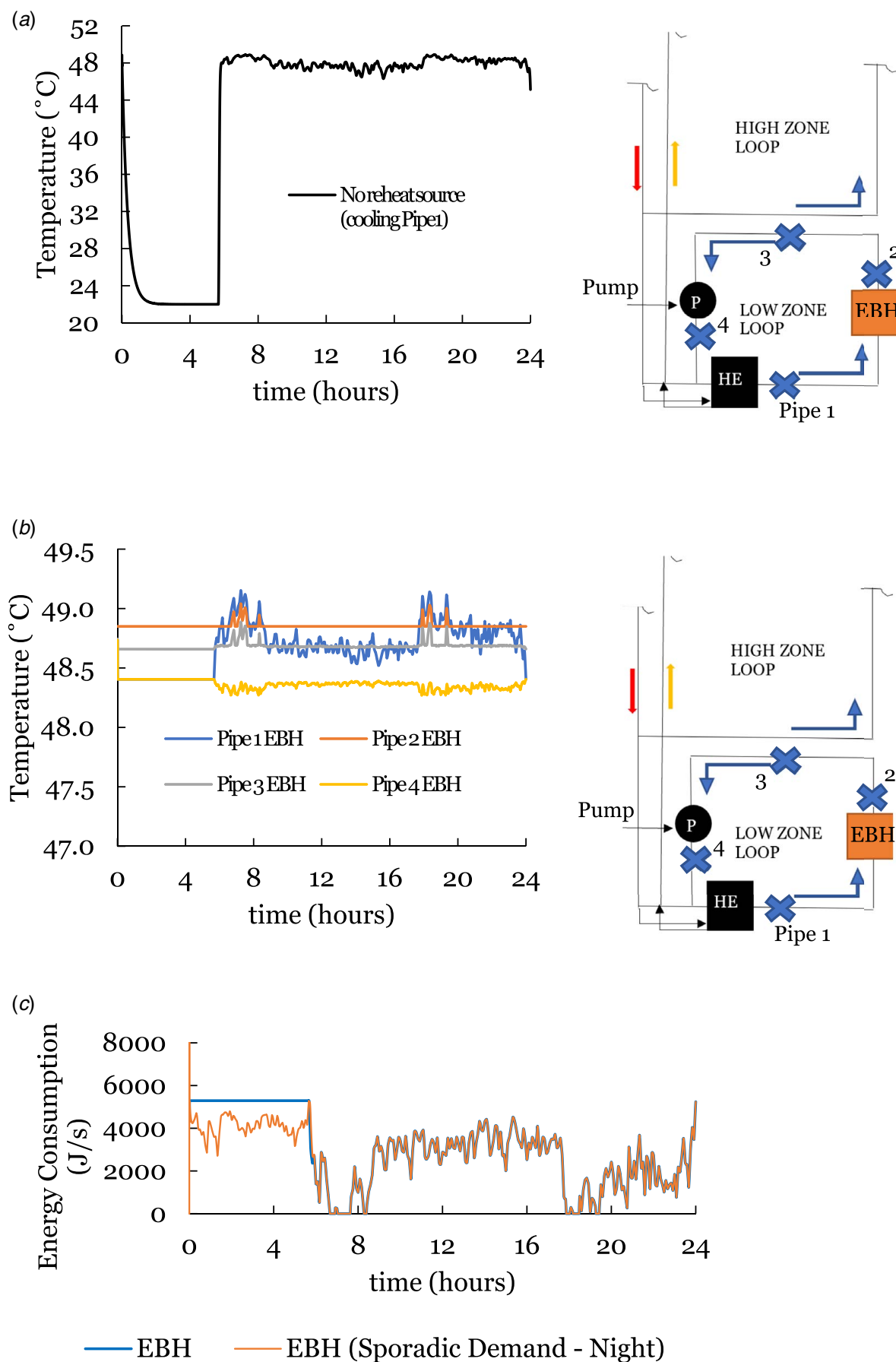


Fig. 9 Electric booster heater (EBH) performance in the low-zone loop: (a) no-reheat source loop temperature (Pipe 1), (b) loop temperatures with EBH, and (c) energy consumption of the EBH

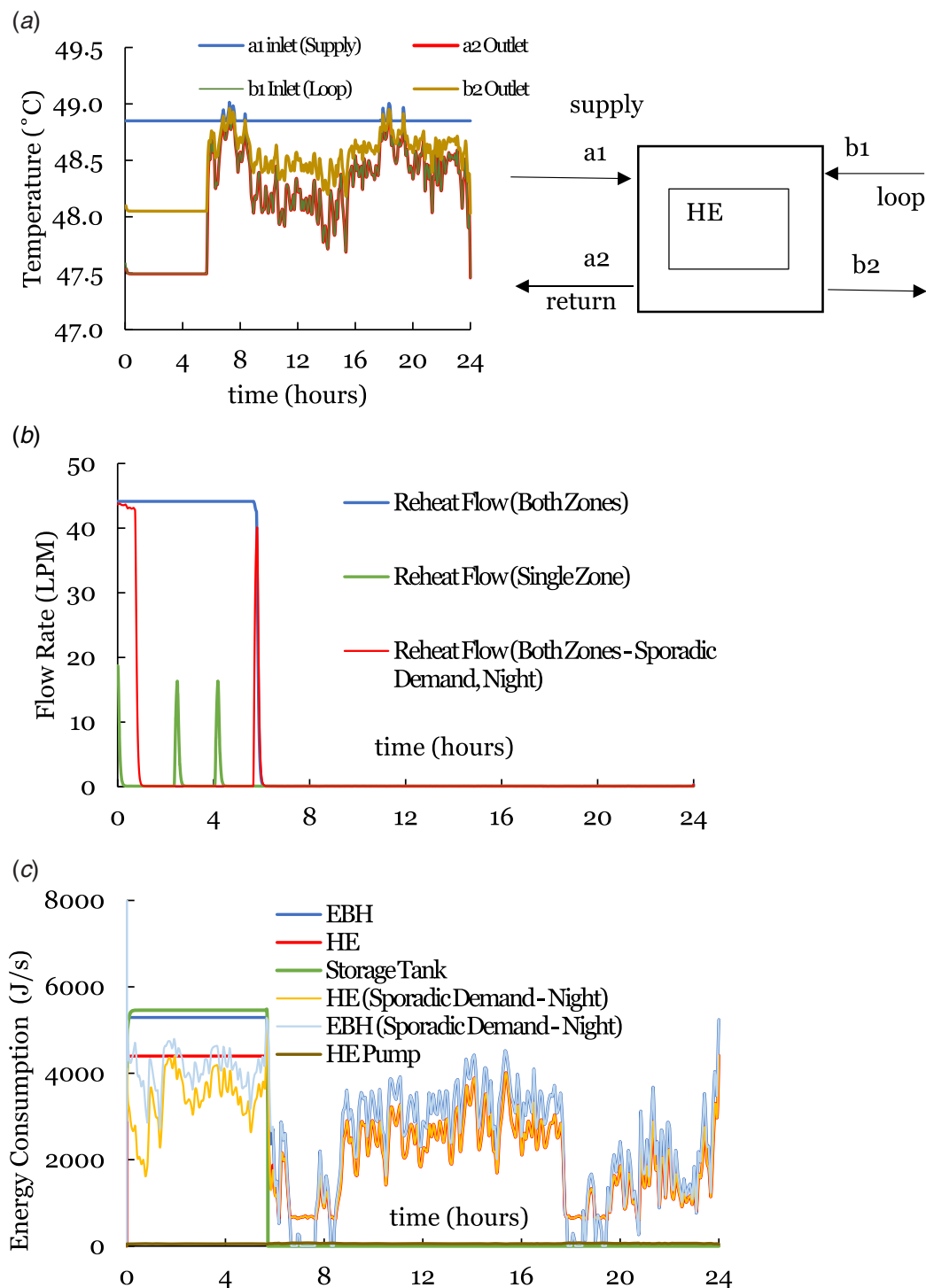


Fig. 10 Heat-exchanger (HE) performance in the low-zone loop: (a) inlet and outlet HE temperatures, (b) reheat flow, and (c) energy consumption (HE and storage tank)

24 h. The increase of reheat flow for the multi-zone configuration is because of additional heat loss from a relatively longer return pipe (which now extends along both zones), increased return mass flow, and heat-exchange inside the HE unit. Considering night demand leads to less reheat flow since there is less heat-exchange in the low-zone loop. The corresponding energy consumption to heat the storage tank is shown in Fig. 10(c). Although there is good agreement between the HE and EBH units, the storage tank's energy consumption during demand is zero. This is also reflected in Fig. 10(b), with no-reheat flow all through demand.

The reason for zero reheat flow during demand is hot-water flow that mixes with the return flow inside the CLI mixing chamber. Figure 11 shows annual energy cost considering both the EBH (based on a rate of 12.8 $\approx$ //kWh [30]) and HE (based on a rate of 7.93 $\text{¢}/\text{m}^3$ or $\approx 1\text{¢}/\text{kWh}$ [31]) installations. The cost for the EBH unit is $\approx$ \$4000/annum to maintain the low-zone temperature at $\approx 49^\circ\text{C}$. A much lower cost (\$100/annum) is found for the HE unit due to zero energy consumption throughout demand and the relatively lower cost of natural gas per kWh. For the sporadic demand case during the night, there is a comparable ratio of the difference in costs.

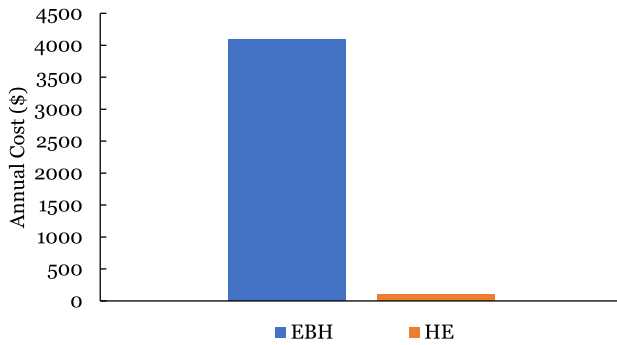


Fig. 11 Annual cost (\$) from the EBH and HE. The annual cost for the HE is based on annual gas consumption to reheat the storage tank.

Conclusion

A single-zone 297-unit OpenModelica (OM) model was compared to field data over 24 h to study the performance of the closed-loop flow circuit. An additional low-zone loop was added to the model to compare energy consumption between a heat-exchanger (HE) and an electric booster heater (EBH).

For the single zone, the results showed the following:

- (1) Good agreement of main supply and return flow between OM and field data, reaching maximum values of ≈ 230 LPM (62 GPM) and 120 LPM (32 GPM), respectively.
- (2) Field data and OM results showed reheat flow reaching ≈ 15 LPM (4 GPM) during nighttime to ensure the distribution network water temperature did not fall below $\approx 45^\circ\text{C}$ (113°F). The profile difference was attributed to valve response time and sporadic demand during nighttime not captured by the model.
- (3) The return flows showed a consistent temperature of $\approx 48^\circ\text{C}$ (118°F) once the reheat valve was closed shut in early morning.

For the multi-zone, the results showed:

- (1) EBH energy consumption $\dot{Q}_{\text{heat}} \approx 5000$ J/s (5 kW) was shown during no-demand (midnight to 6 a.m.) when it cools, and $\dot{Q}_{\text{heat}} \approx 3000$ J/s (3 kW) during midday (i.e., 10 a.m.–4 p.m.) when demand reduces.
- (2) The HE unit as well showed constant energy consumption at no demand and zero during demand, given no-reheat flow as the hot-water flow mixed with the return flow inside the CLI mixing chamber.
- (3) In comparison with a single-zone configuration, additional reheat flow was required for the multi-zone because of additional heat loss from a relatively longer return pipe, increased return mass flow, and heat-exchange inside the HE unit.
- (4) The electricity cost for the EBH unit was $\approx \$4000/\text{annum}$ to maintain the low-zone temperature at $\approx 49^\circ\text{C}$. A much lower cost was found with the HE unit because of no energy consumption throughout demand and a relatively lower cost per kWh.

Authorship Contribution Statement

Marin Vratonjic: Writing—review and editing, Writing—original draft, conceptualization, software, formal analysis, investigation, validation. Ali Rahmatmand: Writing—review and editing, formal analysis, investigation, conceptualization. Pierre

E. Sullivan: Writing—review and editing, supervision, project administration, methodology, and investigation.

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Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The data sets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request. The authors attest that all data for this study are included in the paper. Data provided by a third party are listed in Acknowledgment. No data, models, or code were generated or used for this paper.

Nomenclature

h	= specific enthalpy for liquid water, kJ/kg
G	= pipe conductance, W/K; $(2\pi kL/\log(r_{\text{out}}/r_{\text{in}}))$
L	= length of pipe, m
$\dot{Q}$	= total heat transfer, kW; $(\dot{Q}\Delta t)$
$\dot{m}$	= mass flowrate, kg/s
$\dot{Q}$	= heat energy transferred to water, kW; $(\dot{m}c_p\Delta T)$
c_p	= specific heat of water, kJ/kgK
r_{in}	= inside radius of pipe segment, m
r_{out}	= outside radius of pipe segment, m
Q_{demand}	= demand flowrate, LPM
Q_{max}	= maximum flowrate, LPM
Q_{recirc}	= recirculation flowrate (total flow), LPM; $(Q_{\text{reh}} + Q_{\text{ret}})$
Q_{reh}	= reheat flowrate, LPM
Q_{ret}	= return flowrate (back to the CLI device), LPM
Q^*	= non-dimensional flow rate, $(Q_{\text{demand}}/Q_{\text{max}})$
ΔT	= temperature change, K

Greek Symbols

ϵ^*	= normalized error for flowrate and temperature, respectively; $\epsilon_{\text{OM}}/ \bar{Q} $, $\epsilon_{\text{OM}}/ \bar{T} $
κ	= thermal conductivity coefficient, W/mK

Subscripts or Superscripts

C	= cold
H	= hot
max	= maximum
R	= reheat
recirc	= recirculation
reh	= reheat
ret	= return

Appendix

A complete set of OpenModelica (OM) models are shown in Figs. 12–14.

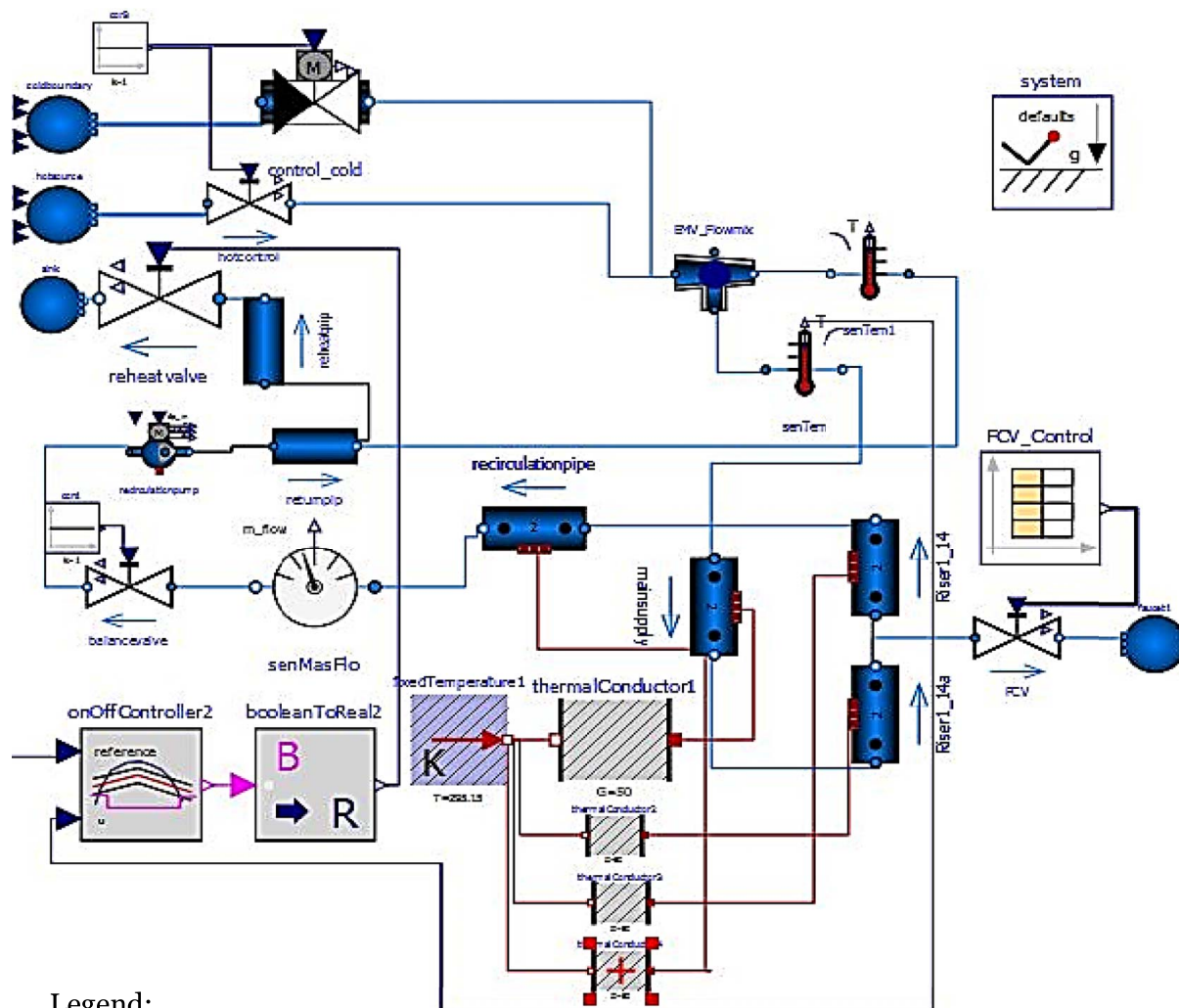
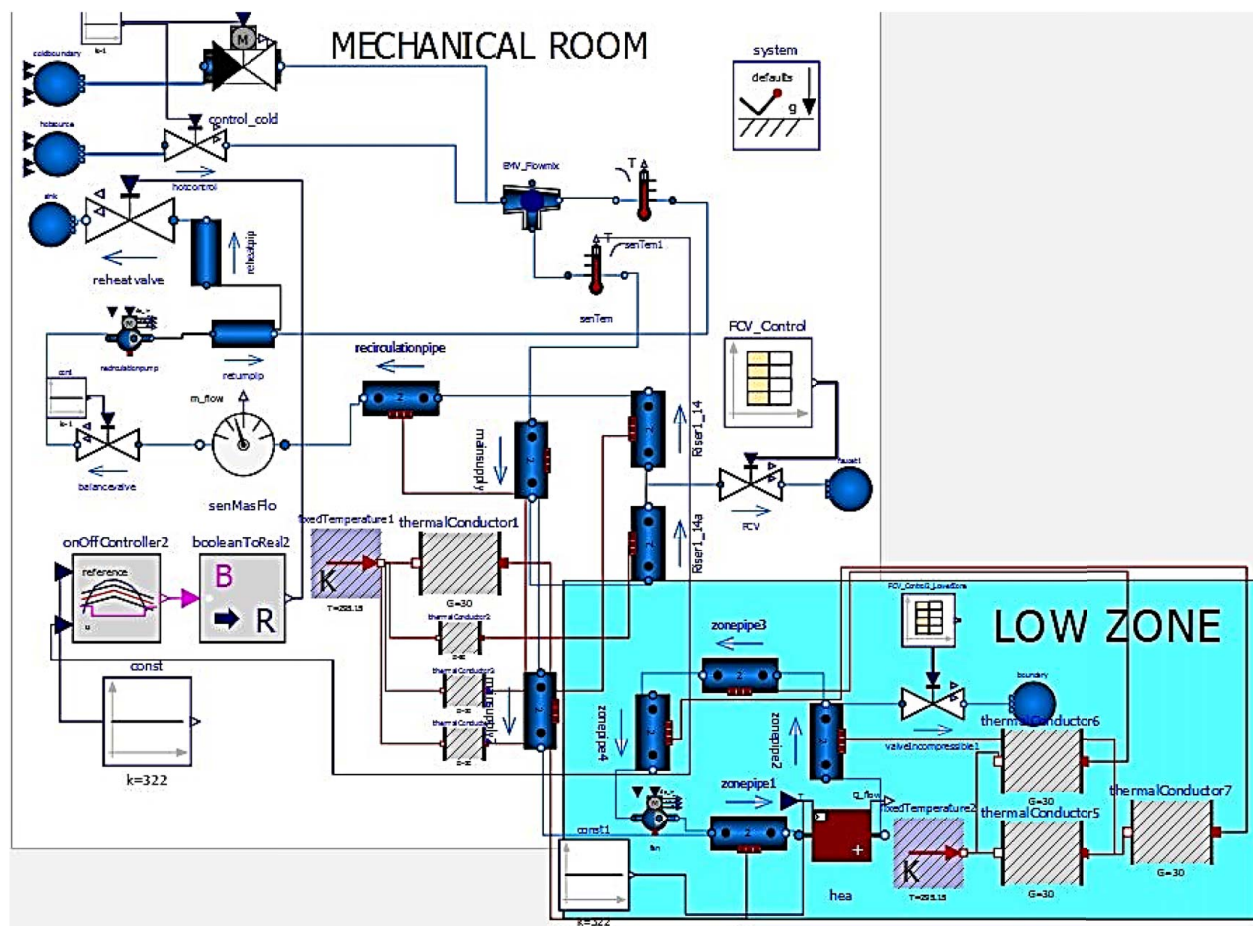


Fig. 12 Comprehensive OM model of the mechanical room (single-zone)



Legend:

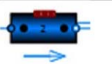
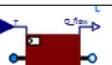
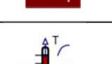
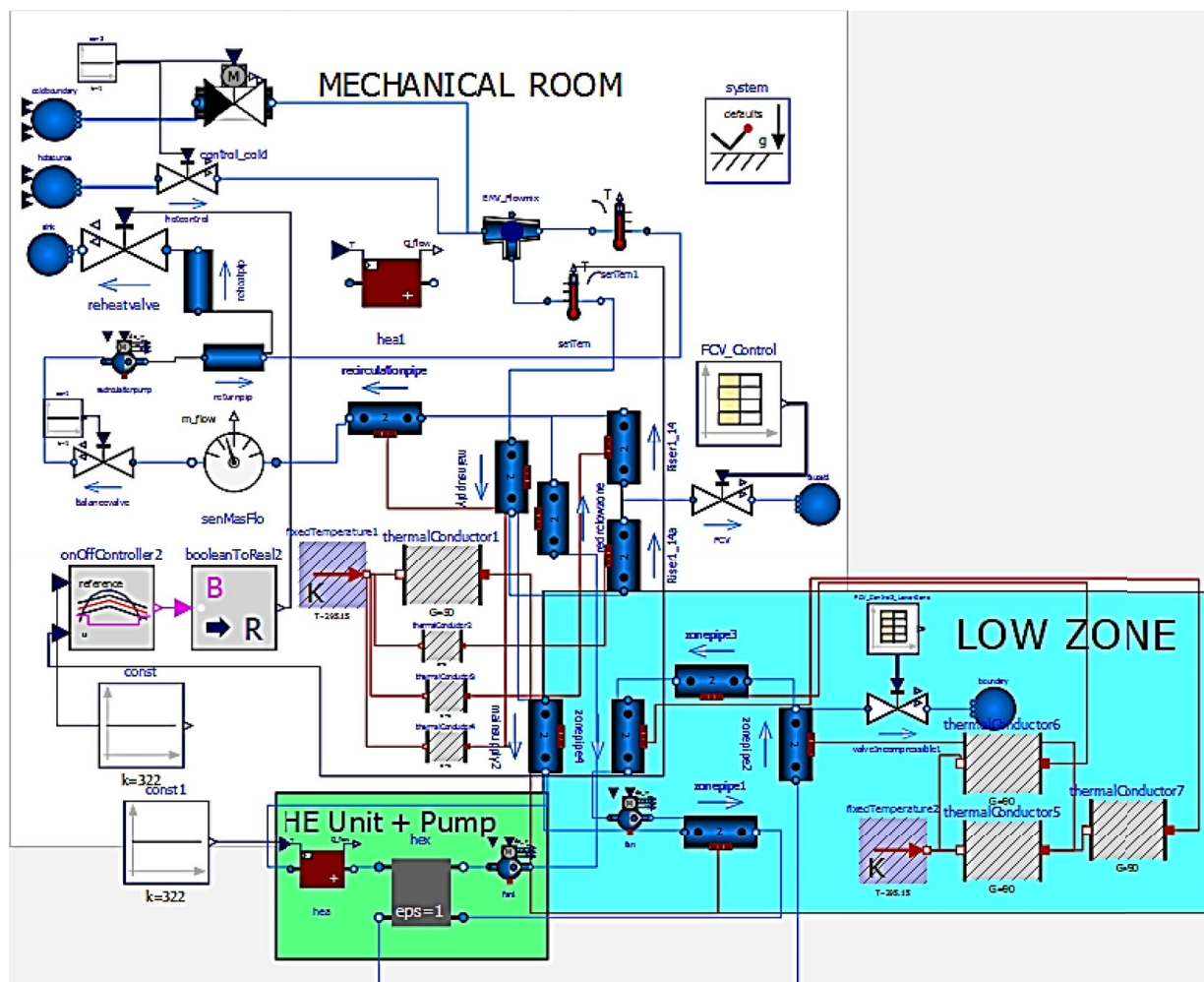
Dynamic Pipe Segment		Branch valve (Two-Way Linear)	
Booster Heater		Conduction Block	
Temperature Sensor		Block components from Fluids and Buildings library - OpenModelica	

Fig. 13 OM model of a multi-zone building with an EBH installation in the low-zone



Legend:

Dynamic Pipe Segment		Branch valve (Two-Way Linear)	
Heat-Exchanger		Conduction Block	
Temperature Sensor		Block components from Fluids and Buildings library - OpenModelica	

Fig. 14 OM model of a multi-zone building with a heat-exchanger Installed in the low-zone

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